ADVANCES IN RUNAWAY ELECTRON CONTROL AND MODEL VALIDATION FOR ITER

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Abstract

Measurements and modeling of runaway electron (RE) dissipation in DIII-D has resolved key experimental discrepancies and validated predictions for ITER, improving confidence that RE mitigation and avoidance can be predictively optimized without empirical tuning. Energy-resolved measurements of hard X-ray (HXR) flux demonstrate that anomalous dissipation of RE beams is strongest for low energy RE populations. Modeling including the self-consistent interaction of the RE population with RE-driven kinetic instabilities reproduces the enhanced dissipation and finds strong wave-particle interactions with the low energy RE population. HXR measurements have also validated RE distribution function ($f_e$) dependencies and observed the effect of phase-space attractors that pile up REs at a given energy. Increasing synchrotron damping shifts the high-energy $f_e$ towards lower energy, though quantitatively observed synchrotron effects are larger than predicted. Increasing collisional damping shifts the full $f_e$ to lower energy. $f_e$ validation in both phase space and real space is further advanced by new synchrotron and bremsstrahlung emission synthetic diagnostics. These tools reproduce experimental images and can validate different pitch-angle distribution models. Considering RE seed formation and final loss, a new method to experimentally estimate the RE seed current from pellet ablation rates reveals that the hot-tail generation mechanism significantly over-estimates RE seed production, while the Dreicer mechanism is insufficient to explain the observed seed. MHz-range kinetic instabilities have also been observed to drive RE loss and possibly inhibit RE plateau formation. Model predictions of first wall Joule heating during the RE final loss are consistent with experiment at high ion charge ($Z$). Discrepancies are found at low $Z$, however, indicating some RE dissipation processes remain poorly understood. The above measurements and comparison with theory substantially improve confidence that model-based optimization of RE avoidance and mitigation can be achieved. This is essential to fully exploit ITER while avoiding RE-induced damage to the first-wall.
1. **Introduction and Motivation**

The runaway electron (RE) problem is of existential concern for fusion-grade tokamaks, as the expected RE multiplication rate increases exponentially with plasma current ($I_p$). Due to the severe potential for damage when REs strike the first-wall, opportunities for empirical tuning of RE mitigation methods will be severely limited. For this reason, predictive modeling plays an especially important role in addressing the RE problem for ITER and beyond. This presentation will describe advances in understanding experimental measurements of RE dynamics and discuss their application to RE mitigation and control. The RE life-cycle can be divided into three phases as shown in Fig. 1, with each having its own challenges to address.

First, the dynamics of the disruption determine the quantity of seed REs and their formation via avalanche multiplication into a mature RE ‘plateau’. The actuator in this phase is the ‘primary’ injection, which both mitigates the thermal quench (TQ) induced thermal and electro-magnetic loads and if possible avoids RE formation. Second, the fully formed RE plateau (potentially carrying MA-level RE currents) can be mitigated via a ‘secondary injection’, ideally dissipating the energy in the plateau quickly. Third, in the ‘final loss’, the incompletely dissipated RE beam can strike the first-wall. This work follows these phases chronologically, describing important advances in each.

2. **RE Seed Formation and Survival**

Considering RE seed formation, a novel technique has been developed to estimate the RE seed current from measurements of enhanced ablation of small Argon (Ar) pellets [1] used to maximize the likelihood of RE production in DIII-D. The technique compares measured Ar-I emission to the expected ablation level from the measured thermal plasma profiles. Any excess Ar-I light is attributed to the RE population further ablating the pellet, yielding an estimate of the RE seed current prior to avalanche multiplication. As shown in Fig. 2, this estimation technique yields RE seed magnitudes of $O(10^3)$ A. This is to be compared to theoretical estimates for the hot-tail mechanism (whereby a residual population of keV electrons is accelerated to become REs prior to thermalization with the rapidly cooling bulk) and the Dreicer mechanism (whereby the large applied electric field accelerates REs from the tail of the thermal distribution). The experimental value is found to be significantly lower than that expected from hot-tail theory, which is expected to be the dominant mechanism in very high $T_e$ tokamaks such as ITER. The Dreicer mechanism is thought to be relatively unimportant both in DIII-D and ITER, and this is confirmed in this study since the experimental values are far in excess of the Dreicer estimate. While no candidate mechanism has been identified, any reduction in the RE seed from hot-tail expectations would be positive for ITER. These studies are further discussed in Ref. [1].
The observed kA-level RE seeds must undergo avalanche multiplication in order to form the quasi-stationary RE plateau. Recent work employing a unique combination of high-frequency magnetic probes and HXR spectrometers has identified a possible mechanism for the commonly observed failure of many discharges to convert their RE seeds into the plateau. As shown in Fig. 3, MHz-level magnetic fluctuations are observed and found to be particularly intense and long-lived in discharges that fail to form plateaus. These MHz-level fluctuations are in turn found to be excited when the maximum RE energy ($E_{RE}$) exceeds a threshold 2.5 MeV, as measured by an HXR spectroscopic diagnostic further described in Sec. 3.3.1. Looking with high time resolution, it can be seen that spikes in distant HXR detectors (indicating RE loss) are preceded by periods of intense fluctuation activity. This indicates the fluctuations are driving RE loss, but whether the loss is solely responsible for preventing plateau formation is still under study.

Variations of the primary injection actuator (Ar pellet and massive gas injection quantity) and pre-disruption $I_P$ are carried out. These find that decreasing the Ar quantity or increasing $I_P$ increases the maximum $E_{RE}$, likely due to an decrease in collisional damping and an increase in available flux, respectively. Counter-intuitively, this increase in max $E_{RE}$ is found to decrease the likelihood of RE plateau formation, presumably due to the excitation of the MHz-level waves. Preliminary studies indicate the observed mode is a compressional Alfven wave (CAW), found at the low frequency extreme of the whistler wave dispersion relation. Since the RE transit frequency ($\approx 16$ MHz) exceeds the wave frequency, the REs perceive the wave as a static three-dimensional magnetic field. Thus, the wave can non-resonantly transport REs to the wall. Extrapolation of these results is still under consideration. These studies are further discussed in Ref. [2], and the relevance to ITER of considering RE-driven kinetic instabilities will be addressed in Sec. 3.3.3.

Figure 3: (a-c) RE plateaus formation is inconsistent, with no plateau cases exhibiting more intense and long-lived MHz-level fluctuations (thought to be a CAW) (d) counter-intuitively RE plateaus can be formed if $E_{RE}$ or available flux is low enough.
3. Controlled RE Dissipation

Attention now turns to the controlled dissipation of the REs. As the plateau stage is quasi-stationary over ≈100 ms, ample time exists to apply secondary mitigating actions to dissipate the plateau prior to the first-wall strike. This section will describe both experiments in DIII-D Ohmic flat-top conditions, where long-duration trace RE beams and availability of standard profile diagnostics enable well-posed model validation studies, as well as experiments in the post-disruption RE plateau regime. Unexpectedly, DIII-D Ohmic flat-top discharges can closely mimic many of the expected non-dimensional parameters of the ITER RE plateau, opening unique opportunities for validation of the RE distribution function (\( f_e \)) and dissipation rates.

3.1. RE Distribution Measurement

Energy-resolved RE measurements are made with a unique tangentially viewing pinhole camera (termed the GRI) equipped with HXR spectrometers viewing each pixel. These measurements are made in the quiescent flat-top of non-disrupting ohmic discharges, where parameters such as electron density (\( n_e \)), electric field (\( E_\varphi \)), \( Z \), and toroidal field (\( B_T \)) are varied to isolate the dependence of \( f_e \) on collisional and synchrotron damping, as well as to bring their non-dimensional values close to what is expected for ITER. Comparing experimental and modeled \( f_e \) evolution in Fig. 4, nearly all qualitative trends are captured [3]. Non-monotonic \( f_e \) features are found at the energy predicted by time-dependent 0-D Fokker Planck modeling (see purple arrows in Fig. 4a,b). These features are formed by the interplay of acceleration via the electric field, drag via electron-electron collisions, pitch-angle scattering via electron-ion collisions, and energy loss via synchrotron radiation. Increasing synchrotron damping by varying \( B_T \) shifts the high-energy \( f_e \) towards lower energy, though quantitatively observed synchrotron effects are larger than predicted. Increasing collisional damping by varying \( n_e \) shifts the full \( f_e \) to lower energy (Fig. 4c,d). Considering information in the spatial domain, energy-dependent radial gradients of the RE population are observed, opening a new frontier in model validation to specifically target RE spatial transport effects. Spatial resolution also yields RE pitch-angle information and verifies that \( f_e \) are more parallel-directed at high energy. These studies are discussed in Ref. [4].

Distribution function validation is further advanced by recently developed synchrotron emission synthetic diagnostics [5, 6]. As seen in Fig. 5, these tools are now able to reproduce experimental synchrotron images and are used to validate different pitch-angle distribution models. As the image shape is very sensitive, different pitch-angle distributions are found based on the input energy distribution. This enables these images to constrain aspects of the distribution function (namely the behavior at high pitch-angle) more easily than the bremsstrahlung measurements shown in Fig. 4.

**Figure 4:** Variation of \( f_e \) in experiment and modeling as collisional and synchrotron damping is varied.

**Figure 5:** Comparison of synchrotron camera experimental images to synthetic diagnostics using two \( f_e \) assumptions.
3.2. RE Dissipation via Kinetic Instabilities

Energy-resolved GRI measurements can also be used to compare RE decay rates to modeling. Previous results had found significant anomalous dissipation in Ohmic flat-top experiments using volumetric RE emission [7]. This was cast in terms of an anomalous value of $E_\phi$ (normalized to the critical electric field, $E_{\text{crit}}$) at which RE emission transitioned from growth to decay. Energy-resolved measurements further clarified this picture by isolating the strongest anomalous dissipation to low energy. The isolation of the anomalous loss to low energy is difficult to explain with spatial transport arguments, since these losses should increase with energy. This led to the hypothesis of kinetic instabilities as the anomalous loss mechanism. Consideration of kinetic instabilities is further motivated by the observation of non-monotonic features in $f_e$, which should be a strong drive for these modes. As shown in Fig. 6a), a recent model treating the effect of RE-driven kinetic instabilities finds a substantial increase in the effective $E_\phi/E_{\text{crit}}$ for RE decay due to the kinetic instability effect [8, 9], bringing modeling and experiment largely into agreement on the effective $E_\phi/E_{\text{crit}}$. Furthermore, quantitative discrepancies between the measured and modeled $f_e$ are decreased when the kinetic instabilities are included, as shown in Fig. 6b). Adding to the evidence for the kinetic instability effect in the Ohmic flat-top plasmas is the direct observation of kinetic instabilities in the whistler range of frequencies ($\approx 100$ MHz), which is described in separate contributions to this conference [10, 11, 12]. However, the instabilities thought to be responsible for the anomalous dissipation are higher in frequency ($\approx 10$ GHz) and cannot be directly observed at present.

![Figure 6: Resolution of experimental discrepancies in (a) RE growth rate and (b) RE distribution function when taking kinetic instability effects into account.](image)

3.3. Future Prospects for ITER of RE Dissipation via Kinetic Instabilities

While the Ohmic flat-top experiments were motivated by their good non-dimensional match to ITER RE plateaus in terms of collisional and synchrotron damping effects, the identification of kinetic instabilities as the dominant anomalous loss mechanism raises new challenges for ITER-relevance. This is because the Ohmic plasmas, with keV-level thermal $T_e$, are much more likely to excite kinetic instabilities due to their weak collisional damping. In contrast, RE plateaus will naturally be rather cold and dense. As shown in Fig. 7 (which is modified from the theory of Ref. [13] for DIII-D conditions), these conditions are poorly suited to excite kinetic instabilities. Use of Ar as a secondary injection actuator further pushes the RE plateau away from the conditions to excite instabilities in the plateau. For this reason, kinetic instabilities have been assumed to be irrelevant for RE dissipation in ITER plateaus. Two recent findings call this assumption into question and potentially open new opportunities for RE control. The first is the finding discussed in Sec. 2, whereby MHz-level instabilities are transiently observed as the plateau is formed despite the cold and dense (i.e., collisional) conditions. This is a subject of active study, but it may be that the very low frequency of these instabilities (below the ion cyclotron frequency) modify the collisional damping requirements such that the waves can be driven in cold and dense conditions.

![Figure 7: Kinetic instability operating space in DIII-D conditions, using the instability theory of Ref. [13]. Modification of RE beam parameters by injection of high-Z and low-Z gas is shown.](image)
A preliminary study of wave-excitation in these collisionless RE plateaus identified two distinct regimes where RE-driven instability is found, as shown in Fig. 8. Both require active modification of the electric field ($E_\phi$), indicating the natural post-$D_2$ collisionless RE plateau is still stable to instability in DIII-D. At very negative $E_\phi$ similar frequency instabilities to those of Sec. 2 are seen, though with highly non-linear chirping behavior. The negative $E_\phi$ (imposed by the Ohmic solenoid) suggests that low RE energies are needed to excite this class of instability. At very high $E_\phi$, a second class of instability is found. Unlike the first, this class strongly affects the non-thermal ECE emission, giving rise to large crashes that registered in many diagnostics (such as $D_\alpha$). Due to the high $E_\phi$, it is likely that this is a classical fan instability - observed for the first time in the RE plateau. While these two conditions are pathological due to the large absolute $E_\phi$, they demonstrate that kinetic instabilities can be excited in the RE plateau after $D_2$ injection. Interestingly, it should be noted that the instabilities in Sec. 2 also existed during periods of very high $E_\phi$ (but without $D_2$ injection). Further work is needed to understand how exploit these modes for RE dissipation using ITER-relevant actuators, or alternatively, how to actively drive them from the wall with antennas.

### 3.4. Impact of RE Plateau Vertical Loss

An additional challenge exists due to the difficulty of superconducting shaping coils to respond to transient changes in plasma conditions. A sudden change in $I_P$ (between the pre-disruptive value and the RE plateau current) of as little as 3 MA is expected to lead to a loss of vertical stability, causing RE plateaus to drift upwards and strike the wall in $\approx 150$ ms if unmitigated. This ultimately sets a time limit for a successful RE secondary injection scheme. DIII-D experiments have recreated this situation by developing vertically elongated RE plateaus and allowing them to drift upwards uncontrollably, as shown in Fig. 9. Repeating this evolution, scans of the Ar secondary injection quantity and timing found that both could reduce the RE current ($I_{RE}$) at the final loss. However, the $I_{RE}$ reduction saturated at a critical Ar quantity, indicating that the amount of Ar assimilated into the beam was also saturated. Ar saturation is under study and is thought to be due to a reduction of neutral diffusion into the beam as the ionization fraction and background temperature decreases [15].

This study was primarily motivated by recent ITER simulations that found increasing the Ar secondary injection quantity increased the vertical loss rate, and thus did not reduce the RE current at the final loss. Importantly, this effect is due to persistent eddy currents in the ITER vessel that are absent in DIII-D due to the much longer ‘wall time’ in ITER (due to conductivity and size differences between the two vessels). Modeling activities are planned to benchmark the ITER simulations with DIII-D data by synthetically modifying the wall time of each device.
4. **Final RE Loss to the First-Wall**

Final consideration is given to predicting the energy deposited to the first-wall in the event of an RE strike. While very undesirable in principle, understanding the energy deposition is of great importance as this will ultimately determine the requirements for a successful RE mitigation scheme. New estimates of Joule heating (magnetic to kinetic energy conversion) during the final RE loss, shown in Fig. 10, are found to vary non-monotonically with Z, peaking at the intermediate Z≈6. A 0-D circuit model describes the basic trends in the data, and is within experimental uncertainty at high Z. However, at low Z (<5), local energy deposition appears around 5-20 times less than expected, suggesting that low-Z RE energy dissipation is not fully understood. These studies are further discussed in Ref. [16].

![Figure 10: Dependence on Z of first-wall heating from REs during the final loss.](image)

5. **Conclusion and Summary**

This work has summarized recent and rapid progress in understanding the mitigation and control of REs for ITER, resolving several key experimental discrepancies and identifying areas for future progress. Consideration of RE seed generation and survival into an RE plateau demonstrates that hot-tail theory is over-estimating the RE seed magnitude, and kinetic instabilities in the MHz-range (likely compressional Alfven waves) are excited that drive some amount of RE loss; possibly enough to prevent RE plateau formation in some conditions. Both of these results have the potential to be positive for ITER. Considering controlled RE dissipation, Ohmic flat-top experiments have qualitatively verified the role of collisional and synchrotron damping on the RE f_e and enabled validation of synchrotron image modeling. Long-standing anomalies in the RE dissipation rate in these experiments have recently been resolved by taking into account kinetic instability effects. These instabilities are particularly likely to be excited in these keV-level T_e Ohmic plasmas, but is unfavorable in the post-disruption RE plateau due to its collisional conditions. Regardless, their observation in the RE seed formation process (despite high collisionality) and in mature RE plateaus (when collisionality is lowered with D2 injection) is surprising and opens new opportunities to dissipate RE energy using naturally excited or externally injected waves. Finally, considering the final loss phase, a model is developed that enables estimation of the energy deposition that is in good agreement for most experimental conditions. The above measurements and comparison with theory substantially improves confidence that model-based optimization of RE avoidance and mitigation can be achieved. This is essential to fully exploit ITER while avoiding RE-induced damage to the first-wall.

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